MARKET ASSESSMENT OF PYROLYSIS PRODUCTS

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ABSTRACT: The PYRAGRAF project is an Innovation Action aimed at advancing sustainability in agriculture and forestry through efficient biomass waste management. Addressing the increasing challenges in these sectors, responsible for 1.5% of European GDP and heavily impacted by climate change, PYRAGRAF introduces a mobile biomass pyrolysis unit powered by concentrated solar energy. This innovative approach enhances the production of biochar, wood vinegar, bio-oil, and pyrolysis gas, supporting a reduced carbon footprint and aligning with circular economy principles. This study provides a comprehensive analysis of the market conditions, stakeholder dynamics, and performance potential for these pyrolysis products within the EU and PYRAGRAF countries (Germany, Poland, Portugal, Sweden and Türkiye). A thorough PESTEL (Political, Economic, Social, Technological, Environmental, and Legal) analysis is conducted, revealing the opportunities and challenges these products may face across different markets. Additionally, the study identifies key stakeholders and their influence on market dynamics, offering insights critical for market penetration and adoption of these sustainable solutions.
Keywords: pyrolysis, stakeholders, market

1 INTRODUCTION

PYRAGRAF project has the ambition to turn the waste and residues from forestry and agriculture into added-value products that allow to enhance sustainability and resilience of these sectors, as well as provide new sources of renewable energy for local communities. This will be achieved by providing a mobile pyrolysis system, composed of three main modules: a solar-assisted gasifier burner, a biomass dryer, and an integrated pyrolysis reactor. The results of the pyrolysis process are four products with different application areas biochar, wood vinegar, pyrogas, and bio-oil. The aim of this report is to holistically assess the markets and conditions needed to successfully commercialise these products, identify possible risks and provide mitigation strategies as well as recommendations supporting the exploitation strategy and further uptake of the proposed solutions in the EU. This report will be updated and improved before the end of the project.

The scope of the market analysis methodology will cover the EU level and selected countries: Portugal, Germany, Türkiye, Poland and Sweden. The report is based on mixed methods approach. In the initial phase, desktop research is used to gather first data required to the analysis. Local conditions and stakeholders for the pyrolysis products have been assessed using PESTEL analysis at both national (Portugal, Germany, Türkiye, Poland, Sweden) and European levels. Besides, an initial detailed analysis of the four pyrolysis products—biochar, bio-oil, pyrolysis gas, and wood vinegar—has been conducted, to better understand each product and strategize their market uptake and positioning. The first version of the report contains also the preliminary analysis of the relevant stakeholders in the selected markets**..**

2 METHODOLOGY

The geographical scope of the analysis covers representatives of four different European regions (North, South-West, East, Central) as well as Western Asia, including countries where the project's demonstrations take place: Portugal, Germany, Türkiye, Poland and Sweden. Such an approach allowed also to incorporate both EU and non-EU member countries' perspective, as well as account for distinct regional conditions. Additionally, the EU level was also included.

There are many methods that may be applied to analyse the market for innovative products. In this project, mixed method approach has been followed to cover adequately all the aspects relevant to the market assessment of the pyrolysis products.

In the first step, to investigate the context of the market activity, the PESTEL analysis was conducted using secondary data sources. PESTEL stands for political, economic, social, technological, environmental and legal factors in the external environment that influence the studied phenomenon, in this case markets for the selected products. Relevant data was gathered from the project partners based in respective countries and the analysis of the EU level was. Similar procedure is followed in the case of stakeholders' identification and regulatory analysis.

3 EXTERNAL CONDITIONS: LOCAL AND EU LEVEL

This chapter delves into a comprehensive analysis of the pyrolysis market in five diverse European countries, being the project's countries: Portugal, Germany, Türkiye, Poland and Sweden. To fully understand the regional characteristics and viability of pyrolysis in these nations, a detailed PESTEL analysis has been conducted, including political, economic, social, technological, environmental, and legal conditions.

Political Conditions: The political environment in each country has an influence on the development and implementation of pyrolysis technology and biomass penetration in general. Under this section governmental policies, regulations, and incentives have been explored. The focus was on national and EU-level frameworks that affect (specifically on bio-) energy production, waste management, and environmental protection.

Economic Conditions: Economic factors are important to understand the feasibility and profitability of pyrolysis products. This segment analyses the economic landscape, including market demand, financial incentives, cost structures, and economic stability.

Social Conditions: The acceptance and support play a significant role in the successful implementation of new technologies. This part of the analysis will examine societal aspects such as population demographics, aging, lifestyle changes, social trends, and potential cultural barriers. Public awareness and community engagement in environmental issues could also be considered.

Technological Conditions: This section will review the current state of technological infrastructure, focusing on innovativeness, R&D activities, R&D funding, and technological awareness on biomass and pyrolysis technologies. It will assess the landscape of each country to support and advance pyrolysis products through innovation and technological development.

Environmental Conditions: This part will evaluate the environmental context, challenges and opportunities in each country, focusing on climate and weather conditions, key natural resources, forests, climate change impacts, and environmental hazards and protection measures.

Legal Conditions: This analysis will cover relevant laws, regulations, and compliance requirements impacting the deployment of pyrolysis technologies. Key areas of focus includes forestry, agriculture, waste management, renewable energy, permits, authorizations, obligatory certification, consumer protection, and other significant legal frameworks at both the EU and national levels.

Following the PESTEL analysis, the chapter will delve into the potential of pyrolysis products in Portugal, Germany, Türkiye, and Poland. Pyrolysis produces valuable outputs such as biochar, wood vinegar, bio-oil, and pyrogas, each with distinct applications in energy, agriculture, and industry. This section will examine the market demand and application areas for these products within the context of each country's unique conditions.

Specifically, the report will cover the following aspects for each product:

1) What is it about?
2) Why is it useful? What are the competitive advantages?
3) Which products will it compete with?
4) How can it be further advanced and improved? What is next? (at the end of the project)
5) Specific notable details, properties, performance levels (amounts of product produced in one unit, product formulation)
6) Specific details about value chain and logistics (i.e., does it need further processing or is it ready to be delivered to the final customer? Who is the direct customer? What are the requirements for transport and storage? Etc.)

4 PESTEL ANALYSIS

EU-Level

The European Union provides a supportive policy base for the development of pyrolysis products, shaped by initiatives such as the Biodiversity Strategy for 2030 [1], the EU Green Deal [2], the Bioeconomy Strategy [3] and Energy Taxation Directive [4]. While pyrolysis products are not always directly referenced, these policies collectively promote bio-based innovations, discourage the use of whole trees and food crops for bioenergy, and support decentralized renewable energy systems. Horizon Europe, as the primary funding mechanism [5], fosters significant research and development in bioenergy technologies including pyrolysis.

Economically, the EU experienced modest growth in 2023 amid high inflation and reduced domestic consumption. Despite these challenges, investment in the bioeconomy is increasing. Employment in these sectors is declining, though productivity is rising, reflecting ongoing mechanization and digital transformation [6].

Socially, the EU faces a shrinking and aging agricultural workforce, with significant gender and education disparities in rural labor. However, public ecological awareness is growing, particularly regarding sustainable consumption and localized food systems. Educational gaps in the agricultural sector may limit the pace of innovation uptake, though policy instruments like the Common Agricultural Policy (CAP) aim to mitigate these limitations.

On the technological perspective, the EU leads global efforts in agri-digitalization and bioeconomy innovation. Advances in remote sensing, AI, and biomass valorization support the uptake of pyrolysis products. Numerous Horizon Europe projects explore biochar and related technologies, promoting interdisciplinary innovation.

Environmentally, the EU's emphasis on biodiversity restoration, soil health, and decarbonization aligns well with the core benefits of pyrolysis products such as biochar. Legally, while the EU provides the framework for renewable energy and waste valorization, implementation remains the responsibility of member states, often resulting in fragmented regulatory landscapes. The Energy Taxation Directive and national-level subsidies further influence biomass markets [4].

Germany [7-13]

Germany's market is influenced by proactive environmental policies and a robust regulatory framework supporting sustainable technologies. Ministries and federal agencies provide not only regulatory oversight but also funding opportunities and incentives for technologies aligned with the bioeconomy, including pyrolysis.

Economically, Germany benefits from a mature bioeconomy with strong public-private collaboration. The country has a stable market for agricultural and forestry biomass, creating conditions for biochar and related pyrolysis outputs. However, cost competitiveness remains a concern, particularly for emerging products such as wood vinegar and bio-oil.

Social acceptance of bio-based products is high, supported by a well-informed population and active civil society. Farmers' and foresters' associations play a key role in biomass supply chains, influencing both demand and regulatory development. This is bolstered by established NGOs and research centers which support innovation and market adoption.

Technologically, Germany is a leader in applied pyrolysis research. Institutions like Fraunhofer and DBFZ contribute to process optimization, product characterization, and value chain integration. The technological maturity of pyrolysis systems is relatively advanced, making Germany a central node in European pyrolysis development.

Environmental priorities such as GHG reduction, soil enhancement, and sustainable waste management align with the benefits of pyrolysis. Legally, Germany has comprehensive frameworks governing bioenergy, waste use, and agricultural products, although the complexity of federal and regional systems can present administrative hurdles for new entrants.

Poland [14-19]

Poland's pyrolysis market is largely shaped by national-level actors, particularly within agriculture. While the country lacks strong federal policies specifically targeting pyrolysis, there is increasing interest in sustainable agriculture and soil enhancement, creating demand for biochar and wood vinegar. Key institutions in agricultural policy and rural development are becoming more engaged with bio-based innovations.

Economically, the market has limited national funding and low investment in biomass valorization technologies. Nevertheless, the agricultural sector is substantial in size, with a diverse base of farmers' associations that could drive biomass supply and demand for pyrolysis products.

From the social perspective, the farming community remains traditional, with varying levels of openness to innovation. However, there is growing interest in organic and sustainable practices, especially among younger and cooperatively organized farmers. NGOs and foundations also contribute to raising awareness of biochar's environmental and agronomic benefits.

Technological infrastructure for pyrolysis is developing, with ongoing support from research institutions like the Institute of Soil Science and Plant Cultivation. However, commercial-scale operations remain limited, and technology transfer remains a key barrier.

Environmental factors such as soil degradation and climate change impacts make pyrolysis solutions particularly relevant, especially biochar. The legal environment is evolving but still fragmented, with unclear or underdeveloped standards for pyrolysis products, particularly regarding their classification and use in agriculture.

Portugal [20-25]

Portugal has a high level of stakeholder activity across multiple levels of governance. Numerous national and regional energy and environmental agencies are involved in promoting circular economy models, particularly in biomass utilization. While pyrolysis-specific legislation is still commensing, broader strategies around renewable energy and climate adaptation support the sector's development.

Economically, Portugal benefits from growing interest in green energy and resource efficiency. However, the domestic market for pyrolysis products is still in an early phase, with relatively few large-scale investments or industrial applications. The country's decentralized administrative structure, however, allows for localized experimentation and policy innovation.

Social awareness of climate change and sustainable agriculture is increasing, particularly in rural areas where farming remains a key economic activity. Farmers' associations are well organized and increasingly engaged in initiatives involving biofertilizers and organic amendments, making them potential drivers of pyrolysis product demand.

Technologically, Portugal is home to a range of actors involved in renewable energy and biomass valorization, although dedicated pyrolysis R&D is limited. Waste valorization centers and universities provide emerging capabilities to support process development and scale-up.

Environmental conditions such as drought, soil erosion, and declining organic matter in soils create urgent demand for soil amendments like biochar. Legally, Portugal has supportive frameworks for renewables and waste management, but the integration of novel products like wood vinegar and pyrogas into the regulatory system remains limited.

Sweden [26-31]

Sweden presents a concentrated but high-value opportunity for pyrolysis, through its bio-refinery and forestry sectors. The country has a limited number of stakeholders but benefits from high levels of specialization and industrial integration, especially regarding bio-oil and biochar from Nordic softwoods.

Politically and economically, Sweden maintains a strong commitment to climate neutrality and bio-based innovation. This is reflected in public investments and industrial partnerships in advanced biomass processing.

Socially, Sweden's population is highly environmentally conscious, and rural development policies emphasize sustainability and self-sufficiency. This is conducive to decentralized technologies like pyrolysis, especially when embedded in forestry value chains.

Technologically, Sweden hosts several industrial-scale initiatives and R&D collaborations in bio-based product development. Companies such as Pyrocell and SCA operate at the interface of industrial forestry and bioenergy.

Environmental drivers are central in Sweden, including forest management, decarbonization, and circular economy imperatives. Legally, the country has a stable and well-defined regulatory system, though the certification of new pyrolysis products may require harmonization with EU directives.

Türkiye [32]

Türkiye's pyrolysis market is emerging within a dynamic but complex political and economic landscape. A wide range of ministries influence the sector, including those responsible for agriculture, environment, energy, and trade. While specific support for pyrolysis is not yet well defined, related sectors such as organic fertilizers, biomass energy, and sustainable farming receive policy attention.

Economically, Türkiye offers a large agricultural base and increasing interest in value-added biomass products. However, inflationary pressures and regulatory uncertainty may affect market stability and investment in novel technologies.

Socially, environmental NGOs, agricultural cooperatives, and professional societies are active in promoting sustainability, although public awareness of pyrolysis remains limited. Academia and research institutions are increasingly involved in applied biochar research, supported by international collaborations.

Technologically, Türkiye has a growing R&D base with multiple universities and private firms exploring pyrolysis applications. However, commercial readiness and integration into value chains remain in early stages.

Environmental degradation, soil infertility, and climate vulnerability make pyrolysis products like biochar particularly relevant. Legally, the regulatory framework is evolving and may pose challenges regarding product approval, classification, and market entry, especially for secondary outputs like wood vinegar and pyrogas.

5 STAKEHOLDER ANALYSIS

Stakeholder analysis is important for the market assessment, because it provides a comprehensive understanding of market demand and acceptance. Stakeholders, including associations, academy, and policy players, offer valuable insights into their needs, preferences, and concerns. This information helps market players to tailor products to meet market demands better. Understanding the needs of these stakeholders enables companies to design and market pyrolysis products that are more likely to succeed in the market.

Nine stakeholder groups have been identified to understand connections and needs: administration bodies, advisory providers, farmers' associations, foresters' associations, main competitors, NGOs, recycling and waste management organizations, RTOs and academia and other groups. By identifying these stakeholders, we gain insights into market demand and acceptance, compliance requirements, potential risks, and new links.

The above-mentioned stakeholders are explained below for a better understanding of their role in the context of pyrolysis market and indicating why they are significant for developing a comprehensive and effective market strategy by explaining their roles.

Administration Bodies

Administration bodies, including regulatory and governmental agencies, play a role in setting regulatory frameworks. They make sure pyrolysis processes comply with environmental regulations, ensure public safety, and contribute to sustainability goals. Engaging with these bodies helps ensure regulatory compliance and can facilitate smoother market entry.

Advisory Providers

Advisory providers include consultants and experts who offer specialized knowledge on market strategies. They need accurate and up-to-date information to provide relevant advice. Their insights can help companies optimize their operations and develop effective market strategies for pyrolysis products.

Farmers' Associations

Farmers' associations represent the interests of farmers who may supply biomass for pyrolysis. They require assurance that participating in the pyrolysis supply chain will be economically beneficial and sustainable. They also need information on the benefits and applications of pyrolysis products.

Foresters' Associations

Foresters' associations represent those involved in forest management and wood production, potentially supplying woody biomass for pyrolysis processes. Similar to farmers' associations, they need to understand the economic and environmental benefits of pyrolysis.

Main Competitors

Competitors in the market for pyrolysis products and related technologies influence market dynamics through their strategies, innovations, and pricing. It is important to understand their strengths, weaknesses, opportunities, and threats to position pyrolysis products effectively.

NGOs

NGOs, particularly those focused on environmental protection and sustainability, can influence public perception and regulatory policies. Collaborating with NGOs can improve public support for pyrolysis technologies.

Recycling and Waste Management Organizations

These organizations manage the collection, processing, and disposal of waste materials, which could be used as feedstocks for pyrolysis. Linking with these organizations can provide a secure, steady supply of feedstocks.

RTOs and Academia

Regulatory and Trade Organizations (RTO)s and academic institutions conduct research and development on pyrolysis technologies, providing scientific and technological advancements.
They need funding and collaboration opportunities to continue their research. Partnering with these institutions can lead to innovative solutions and improvements in product quality.

Other Groups

This category includes financial institutions, investors, local communities, and social groups that might have a stake in the development of pyrolysis technologies.
To better understand the connections and needs of these stakeholders in the frame of pyrolysis products market, a detailed table has been created. All regional partners have contributed to the creation of this stakeholder overview.

This table categorizes stakeholders based on their geographical level (international, national, and local/regional) and their respective countries, including Germany, Poland, Portugal, Sweden, and Türkiye or EU level. This categorization helps in identifying specific stakeholders in PYAGRAF countries and understanding their specific needs, contribution and influence on the market. Below, the main stakeholder groups for each country are explained as well as EU level.

At the European level, key stakeholders contribute by financing sustainable agriculture, promoting carbon farming, and bridging scientific research with agricultural engineering practices. These organizations support the development of pyrolysis products through investment, knowledge exchange, and collaborative platforms. Their influence spans across EU member states, driving research, standardization, and innovation in sustainable agriculture and biochar usage.

Germany

Germany has a comprehensive and structured landscape supporting pyrolysis products. The country's administrative bodies play a central role, providing strong policy frameworks and funding channels aligned with environmental and bioeconomy goals. There is also a robust presence of farmers' and forestry associations, which support adoption on the ground. Germany boasts a competitive private sector producing pyrolysis systems and biochar, complemented by major research institutions that enhance innovation and technical capacity. Environmental NGOs also contribute through advocacy and policy influence.

Poland

In Poland, the stakeholder environment is strongly centered on national-level farmers' associations and administrative bodies, which influence agricultural policies and implementation strategies. Advisory centers and research institutes support technological innovation and policy development for sustainable agriculture. The ecosystem is geared toward practical agricultural support and knowledge dissemination, with NGOs and networks contributing expertise and community-level outreach.

Portugal

Portugal features a high concentration of administrative bodies and farmers' associations, with many operating at regional levels. This decentralized structure supports regional sustainability initiatives and energy transitions. Stakeholders range from government agencies to energy and agricultural organizations, fostering the adoption of pyrolysis products in climate action and rural development. The market also includes renewable energy companies and NGOs, working on circular economy models and environmental sustainability. Research and innovation are supported through specialized centers focused on waste valorization.

Sweden

Sweden's stakeholder landscape is more concentrated but includes key players in biorefinery and forestry, emphasizing the industrial application of pyrolysis by-products. These organizations are active in the biofuel and biomass value chains, supported by a national farmers' network that connects agricultural stakeholders. The focus is on resource efficiency and bio-based economy strategies, utilizing Nordic biomass for high-value bio-products.

Türkiye

Türkiye has a diverse and multi-sectoral stakeholder ecosystem, with strong administrative involvement from various ministries shaping national policy. The private sector is active in organic fertilizers, biomass energy, and agro-technologies, while NGOs and professional societies play a vital role in ecological advocacy, education, and technical expertise. The academic sector also contributes significantly, supporting R&D through universities. This diverse composition facilitates comprehensive support for sustainable agricultural practices and emerging markets like pyrolysis.

6 PRODUCT ANALYSIS

Biochar

Biochar, according to the definition of the European Biochar Certificate, is a carbon-based, porous material that is produced by biomass pyrolysis - a process whereby organic materials are broken down at temperatures ranging from 350°C to 1000 °C in the absence or low presence of oxygen and usually atmospheric pressure and is applied in such a way that the contained carbon remains stored as a long-term C sink or replaces fossil carbon in industrial manufacturing. Biochar is defined by its quality characteristics, by the raw materials used, its sustainable production and end use [33].

The main properties of biochar include large surface area, high porosity, functional groups, high cation exchange capacity, stability. Moreover it is characterized by high pH, which can help neutralize acidic soils, and it can retain nutrients, reducing their leaching and improving soil fertility.

The main advantages cover renewability, ease and cost-effective preparation, eco-friendliness, reusability [34]. Moreover, biochar production can help sequester carbon, reducing greenhouse gas emissions and mitigating climate change. It can also decrease soil erosion, enhance microbial activity, and improve soil water retention.

Applications and competitive advantages

The broad scope of different functionalities and properties of biochar make it suitable for various applications. Currently, biochar is used as alternative fuel [35], low-cost adsorbents [36], biofertilizers [37], soil quality enhancers [38], precursors of activated carbon [39], catalysts [40] and for many material applications [41]. By substituting biochar for fossil fuels, greenhouse gas emissions can be reduced, and costs can be minimized. Additionally, biochar can lower wastewater treatment costs by being used as a low-cost adsorbent made from various waste streams by thermochemical methods. Biochar's high surface area and porosity make it highly effective for adsorbing pollutants from water, including heavy metals and organic contaminants [42]. Its application as a soil amendment also improves soil structure, water-holding ability, and nutrient retention, which as a consequence promote plant growth and decrease the need of chemical fertilizers application.

As a biofertilizer, biochar improves soil microbial activity and promotes healthier root growth in plants. Moreover, thanks to the biochar versatility it can be further apply as a catalyst for various chemical reactions as well as precursor for activated carbon, which is valuable in industrial filtration processes. Its role in material applications includes use in composites, construction materials, and even in improving asphalt properties [43].

Wood Vinegar

Wood vinegar, also known as pyroligneous acid, is a smoke condensed byproduct of wood-waste pyrolysis [44]. It typically has a brown or reddish yellow color due to a complex mixture of polar and non-polar chemicals with different molecular weights and compositions with water being the major constituent (80–90%) [45].

It mainly consisted of aliphatic, aromatic, and naphthenic hydrocarbons and other oxygenated compounds such as alcohols, aldehydes, ketones, furans, acids, phenols and ethers [46]. Additionally there are many beneficial compounds that can be found in wood vinegar including organic acids, which can improve soil health by lowering soil pH and act as a natural pesticide and fungicide. It can also promote the growth of advantageous microorganisms in the soil.

Applications and competitive advantages

Wood vinegar has been utilized in agriculture as a bio-preservative [47], organic fertilizer [48], herbicide [49], pesticide [50], and fungicide [51]. It has also been used to increase plants' resistance to stress [52]. Because of its antioxidant and antibacterial qualities, numerous research has shown its benefits [53]. Wood vinegar is a biofertilizer and bioherbicide produced as a byproduct of the pyrolysis of biomass waste. At the same time as it reduces costs with the use of chemical fertilizers and herbicides, it reduces the environmental impact by applying an organic product produced through the recovery of agricultural waste. Furthermore, wood vinegar can improve the health of the soil by reducing pH and enhancing nutrient availability, which foster a better growing conditions for plants. It also helps in controlling soil-borne diseases and pests, leading to healthier crops with reduced reliance on synthetic chemicals. The presence of acetic acid and other organic acids in wood vinegar contributes to its ability to suppress weed growth and act as a natural herbicide. One of wood vinegar's competitive advantages is its ability to increase soil microbial activity which helps plants absorb nutrients more effectively and promotes healthier root development. Its multi-functional nature allows it to be used in various agricultural applications, making it a versatile and cost-effective solution. Wood vinegar's production from waste biomass also contributes to a circular economy, reducing waste and promoting sustainable agricultural practices. Furthermore, its effectiveness in small quantities makes it an economical choice for farmers looking to reduce input costs and improve crop resilience [54].

Bio-oil

Bio-oil is a liquid byproduct of fast pyrolysis, a process consisting in rapid heating of biomass in an inert atmosphere. The liquid consists in an emulsion containing oxygenated hydrocarbons, polymers and water, has acidic properties, is immiscible with water or petroleum derivatives, and exhibits both physical and chemical unstable characteristics. Its acidic features make it corrosive. It also releases an acrid smoky odor. Furthermore, it presents typically a dark brown color, a high viscosity (compared to fuel oils), and a relatively high calorific value. In terms of elemental composition, bio-oil is similar to most lignocellulosic biomasses.

Applications and competitive advantages

Bio-oil can be further processed to produce biofuels for energy purposes or in fields connected to the synthesis and extraction of new chemical products or materials (e.g., pyrolytic sugars and lignin) due to their liquid nature and significant calorific value. Additionally, compared to the use of fossil-based feedstocks, the use of biomass residues, including forestry and agricultural wastes, in the manufacture of bio-oils contributes to reduce greenhouse gases (CO2) emissions.

Pyrogas

Pyrolysis gas (pyrogas) is a product of biomass pyrolysis with similar elemental characteristic to biochar and pyrolysis oil [55]. Pyrogas is composed of the non-condensable gaseous fraction produced during pyrolysis, which is mainly a mixture of H2, hydrocarbon gases (C1-C4), CO, CO2, CH4 along with smaller amounts of other trace gases. The exact composition can vary depending on several factors, including the type of feedstock, the temperature at which pyrolysis occurs, the heating rate, the specific conditions within the pyrolysis reactor and the pyrolysis technology. Due to the presence of combustible components, pyrogas is also recognized to possess significant calorific value.

Applications and competitive advantages

The pyrolysis gas may be used as an energy gas for electricity and heat production (incl. for the pyrolysis process itself) or for syngas application depending on the scale of the pyrolysis process [56]. Additionally, pyrogas can be used in sectors related to the production and extraction of novel chemical products or materials (e.g., synthetic natural gas and other chemical compounds). Furthermore, the utilization of biomass feedstocks including forestry and agricultural wastes in the production of pyrogas results in reducing the greenhouse gases emissions, compared to the use of fossil-based feedstocks.

7 CONCLUSIONS

The market analysis conducted in this report shows promising opportunities as well as challenges for the adoption of pyrolysis products in the EU and PYRAGRAF countries. Political frameworks across these regions show varying degrees of support for renewable energy and environmental sustainability, influencing the regulatory landscape for pyrolysis technologies. Economically, there is growing interest and investment in sustainable solutions, although market demand and financial incentives differ among countries. Socially, a positive trend towards environmental awareness and acceptance of sustainable technologies. Technological advancements and R&D activities present opportunities to innovate and improve pyrolysis products, ensuring competitiveness and scalability. Environmental conditions highlight varying climates and natural resource availability, impacting the feasibility and environmental benefits of pyrolysis products. Legal frameworks, while supportive of renewable energy, exhibit complexities in waste management, certification, and compliance requirements.

As the next steps focus group interviews and quantitative surveys will be employed in the upcoming versions. Additionally, market analysis will be expanded, and potential risks will be estimated. These analyses result in strategic recommendations on actionable strategies for each product.

Stakeholders—from administrative bodies and advisory services to farmers' groups and non-governmental organizations—should work together to overcome regulatory difficulties, improve market education, and promote innovation to fully utilize pyrolysis products. By staying proactive and informed, stakeholders can effectively navigate the complexities of this dynamic market.

8 REFERENCES

[1] EU Biodiversity Strategy for 2030. Available: https://environment.ec.europa.eu/strategy/biodiversity-strategy-2030_en

[2] EU Green Deal. Available: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

[3] Bioeconomy Strategy. Available: https://research-and-innovation.ec.europa.eu/research-area/environment/bioeconomy/bioeconomy-strategy_en

[4] Energy Taxation Directive. Available: https://taxation-customs.ec.europa.eu/green-taxation-0/revision-energy-taxation-directive_en

[5] Horizon Europe funding call. Available: https://cinea.ec.europa.eu/funding-opportunities/calls-proposals/horizon-europe-eur-161-million-available-projects-sustainable-secure-and-competitive-energy-supply_en

[6] Eurostat & ECB economic indicators. Available: https://economy-finance.ec.europa.eu

[7] National Bioeconomy Strategy (PtJ). Available: https://www.bmel.de/EN/topics/sustainability/bioeconomy.html

[8] Environmental Report of Germany 2019 (BMUV). Available: https://www.bmuv.de

[9] KPMG Economic Key Facts. Available: https://home.kpmg/de/en/home/insights.html

[10] Fraunhofer Bioeconomy Roadmap. Available: https://www.fraunhofer.de/en/research-fields/bioeconomy.html

[11] German Circular Economy Act (Kreislaufwirtschaftsgesetz). Available: https://www.bmuv.de/gesetz/kreislaufwirtschaftsgesetz

[12] Destatis statistics. Available: https://www.destatis.de
[13] Bioökonomie.de – German Bioeconomy Platform. Available: https://biooekonomie.de
[14] Strategy for Sustainable Development of Rural Areas 2030. Available: https://www.gov.pl/web/rolnictwo
[15] Roadmap for Circular Economy Transformation. Available: https://www.gov.pl/web/klimat
[16] Act on Renewable Energy Sources (2015). Available: https://isap.sejm.gov.pl
[17] Waste Act (2012). Available: https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20120000021/U/D20120021Lj.pdf
[18] Water Act (2017). Available: https://isap.sejm.gov.pl
[19] Fertilizers and Fertilization Act. Available: https://isap.sejm.gov.pl
[20] Urban Waste Strategic Plan 2030 (PERSU 2030) – APA. Available: https://apambiente.pt
[21] National Strategy for Forests (ENC). Available: https://dre.pt/dre/detalhe/resolucao-conselho-ministros/6-b-2015-66432466
[22] Action Plan for Biomethane (2024–2040). Available: https://www.portugal.gov.pt
[23] Blue Bioeconomy Roadmap. Available: https://www2.ciimar.up.pt/pdfs/resources/roadmap digital_hGBit_.pdf
[24] Portugal 2030 Recovery Plan. Available: https://www.portugal2020.pt
[25] REDcert Certification & Decree Law 84/2022. Available: https://www.dqsglobal.com/pt-pt/certifique/certificacao-redcert
[26] Swedish Agricultural Agency Regulation (SJVFS 2006:37). Available: https://jordbruksverket.se
[27] Swedish Forestry Law. Available: https://www.skogsstyrelsen.se
[28] Sweden's Integrated Energy and Climate Plan. Available: https://www.government.se
[29] Statistics Sweden (SCB) & Riksbank. Available: https://www.riksbank.se
[30] Swedish National Waste Management Guidelines. Available: https://www.naturvardsverket.se
[31] Soil Protection and Land Use Law (Law No. 5403). Available: https://www.fao.org/faolex/results/details/en/c/LEX-FAOC024830/
[32] Agricultural Drought Combat Strategy (2008–2027). Available: https://www.tarimorman.gov.tr
[33] EBC (2012-2023) 'European Biochar Certificate - Guidelines for a Sustainable Production of Biochar.' Carbon Standards International (CSI), Frick, Switzerland. (http://european-biochar.org). Version 10.3 from 5th Apr 2022. Available: http://european-biochar.org
[34] Yaashikaa, P. R., Kumar, P. S., Varjani, S. & Saravanan, A. A critical review on the biochar production techniques, characterization, stability and applications for circular bioeconomy. Biotechnology Reports 28, e00570 (2020). Available: https://doi.org/10.1016/j.btre.2020.e00570
[35] Theppitak, S. et al. Comparison on solid biofuel production from wet and dry carbonization processes of food wastes. Appl Energy 272, 115264 (2020). Available: https://doi.org/10.1016/j.apenergy.2020.115264
[36] Abid, N. et al. Biochar from olive mill solid waste as an eco-friendly adsorbent for the removal of polyphenols from olive mill wastewater. Chemical Engineering Research and Design 181, 384–398 (2022). Available: https://doi.org/10.1016/j.cherd.2022.01.002
[37] Jiang, Y., Zhang, X., An, L. & Liu, Y. A novel biochar-augmented enzymatic process for conversion of food waste to biofertilizers: Planting trial with leafy vegetable. Bioresour Technol 399, 130554 (2024). Available: https://doi.org/10.1016/j.biortech.2023.130554
[38] Yuan, Y. et al. Biochar as a sustainable tool for improving the health of salt-affected soils. Soil & Environmental Health 1, 100033 (2023). Available: https://doi.org/10.1016/j.seh.2023.100033
[39] Colomba, A., Berruti, F. & Briens, C. Model for the physical activation of biochar to activated carbon. J Anal Appl Pyrolysis 168, 105769 (2022). Available: https://doi.org/10.1016/j.jaap.2022.105769
[40] Du, J. et al. Study on thermochemical conversion of triglyceride biomass catalyzed by biochar catalyst. Energy 277, 127733 (2023). Available: https://doi.org/10.1016/j.energy.2023.127733
[41] Jafari, A. & Sadeghian, P. Influence of biochar and recycled gypsum on the strength and microstructure of conventional and sustainable cementitious composites. Constr Build Mater 408, 133715 (2023). Available: https://doi.org/10.1016/j.conbuildmat.2023.133715
[42] Janiszewska, D. et al. Activated biochars derived from wood biomass liquefaction residues for effective removal of hazardous hexavalent chromium from aquatic environments. GCB Bioenergy 13, 1247–1259 (2021). Available: https://doi.org/10.1111/gcbb.12815
[43] Lehmann, J. & Joseph, S. Biochar for Environmental Management: Science, Technology and Implementation. (Routledge, 2015).
[44] Mhamdi, R. Evaluating the evolution and impact of wood vinegar research: A bibliometric study. J Anal Appl Pyrolysis 175, 106190 (2023). Available: https://doi.org/10.1016/j.jaap.2023.106190
[45] Petchpoung, K. et al. Predicting antioxidant activity of wood vinegar using color and spectrophotometric parameters. MethodsX 7, 100783 (2020). Available: https://doi.org/10.1016/j.mex.2020.100783
[46] Grewal, A., Abbey, Lord & Gunupuru, L. R. Production, prospects and potential application of pyroligneous acid in agriculture. J Anal Appl Pyrolysis 135, 152–159 (2018). Available: https://doi.org/10.1016/j.jaap.2018.06.011
[47] Xue, R., Zhang, W., Wang, Z.-P. & Zhu, M.-Q. Refining of Eucommia ulmoides Oliver derived wood vinegar for excellent preservation of the typical berries. LWT 174, 114415 (2023). Available: https://doi.org/10.1016/j.lwt.2023.114415
[48] Yuan, Y. et al. Co-application of biochar and pyroligneous acid improved peanut production and nutritional quality in a coastal soil. Environ Technol Innov 28, 102886 (2022). Available: https://doi.org/10.1016/j.eti.2022.102886
[49] Liu, X. et al. The use of wood vinegar as a non-synthetic herbicide for control of broadleaf weeds. Ind Crops Prod 173, 114105 (2021). Available: https://doi.org/10.1016/j.indcrop.2021.114105
[50] Anokye, R., Boadu, K. B., Fianko, C. N. &

Amegashiti, V. B. The chemical composition of Savannah bamboo (Oxytenanthera abyssinica) vinegar at varying pyrolysis temperatures and its termiticidal activity against wood-feeding termites. Advances in Bamboo Science 6, 100063 (2024). Available: https://doi.org/10.1016/j.advbamsci.2024.100063

[51] Pertile, G. & Frąc, M. The Antifungal Effect of Pyroligneous Acid on the Phytopathogenic Fungus Botrytis cinerea. Int J Mol Sci 24, 3080 (2023). Available: https://doi.org/10.3390/ijms24043080

[52] Ma, J. et al. Wood vinegar induces salinity tolerance by alleviating oxidative damages and protecting photosystem II in rapeseed cultivars. Ind Crops Prod 189, 115763 (2022). Available: https://doi.org/10.1016

[53] da Silva, B. A. et al. Use of a product based on wood vinegar of Eucalyptus clone I144 used in the control of bovine mastitis. Vet Microbiol 279, 109670 (2023). Available: https://doi.org/10.1016/j.vetmic.2022.109670

[54] Mohan, D., Sarswat, A., Ok, Y. S. & Pittman, C. U. Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent – A critical review. Bioresour Technol 160, 191–202 (2014). Available: https://doi.org/10.1016/j.biortech.2014.01.120

[55] Sun, Y. et al. Effects of feedstock type, production method, and pyrolysis temperature on biochar and hydrochar properties. Chem Eng J 240, 574–578 (2014). Available: https://doi.org/10.1016/j.cej.2013.10.081

[56] Lappas, A. Biomass pyrolysis in a circulating fluid bed reactor for the production of fuels and chemicals. Fuel 81, 2087–2095 (2002). Available: https://doi.org/10.1016/S0016-2361(02)00156-6

9 ACKNOWLEDGEMENTS

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